"Analytical Study of Tunable Bilayered-Graphene Dipole Antenna"

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Background:

In the last decade, carbon allotropes have attracted the attention of the scientific community, first with carbon nanotubes and, since its isolation in 2004, with graphene, which has shown unique electronic and physical properties, such as unconventional integer quantum hall effect, high carrier mobility at room temperature, and potential for a wide range of applications, like nanoribbon FETs[1]. The excellent transport properties of single and multilayer graphene hold promise to build ultrafast transistors with excellent on state characteristics. However, the lack of significant band gap in such systems has been one of the major roadblocks to achieve low off state current and hence high on/off current ratio. Recently, it has been found, both theoretically and experimentally, that a band gap can be opened up in a bilayer graphene (BLG) using an external bias [3]. Recently, theoretical models and experiments have shown that bilayer graphene has the interesting property of an energy gap tunable with an applied vertical electric field [1].

While the industry is progressing on making graphene a robust semiconductor to replace the other organic and inorganic semiconductors, graphene can also be implemented as a semiconductor antenna. Such applications would not necessarily be limited to the utilization of graphene in the ground plane of antenna structures as has been the focus of much of the current research, but rather focusing on utilization of graphene transmission line structures for antenna applications. Such antenna configurations can be integrated readily with other semiconductor devices in various applications including high-resolution airborne radar [2].

Objectives:

The focus of this research is the mathematical study of the characteristics of a planar microstrip dipole antenna with a bilayer graphene semiconductor as the transmission line. In any microstrip structure, there is a transmission layer, dielectric layer, and ground layer. In this study, there will be a high impedance metal layer on top of the transmission line in segments along the length of the antenna. Like a double gate contact of a MOSFET transistor, this high impedance layer and ground plane will provide a vertical electric field to create a bandgap in the BLG layer. This study will use bandgap tuning in the BLG to provide theoretical data on tuning a dipole antenna in different sequences along the antenna length. Selected sequences will be chosen in this study to determine the change in radiation patterns and magnitudes in the far field region The results of the data in this paper can benefit radar, munition proximity fuzes, and mobile wireless communication devices. This study will use experimental data from [4] to provide bandgap change due to electric displacement.

Design and Structure:

The design of the antenna involves a two atom thick sheet of carbon known as bilayer graphene. The graphene is used as a transmission line on a half wavelength 15 GHz dipole microstrip antenna. The length of the antenna and wavelength were chosen considering the size of BLG material available in today's industry. The BLG transmission layer is separated from the high impedance contact top layer and the ground plane by a1 nanometer thick dielectric material with a dielectric constant of 1.8, as shown in Figure 1 (right). The width of

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14. ABSTRACT
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15. SUBJECT TERMS
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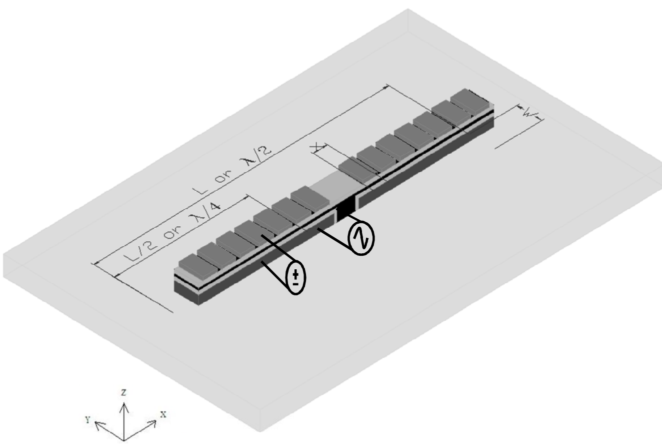
the antenna is 1,000 micron. The high impedance contact layer on top of the BLG is divided along the length of the antenna into 310.0 micron segments separated by 2.5 micron wide gaps between each contact in the x-axis as shown in Figure 1 below. The ground plane of antenna provides the coupling and grounding of the high frequency signal, as well as the grounding of the DC bias voltage. The material of the ground plane is a low impedance metal for reflection.

The gaps will be considered negligible in this study for simplifying calculations, and because the gap is 1/8,000th of a wavelength. Each "x" segment will be calculated in the next section of this study as 312.5 microns for the unit length. The dipole gap at the center of the transmission line is 312.5 microns wide. Figure 1 displays a portion of the 32 total impedance contacts along the length of the antenna. The quantity of 32 was chosen to easily control the tuning of the antenna and contribute to future applicable tuning like: 32 Bit digital tuning and PCM (Pulse Code Modulation). Since the quantity of the high impedance gate contacts determines the unit length calculations, the disadvantage will mean fewer data points.



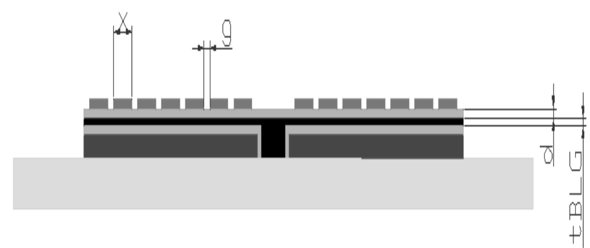


Figure 1, (left) isometric view of microstrip BLG dipole antenna with center bottom feed of high frequency signal and DC biasing of top contacts and ground, (right) front view section cut of the bilayered graphene microstrip dipole antenna

Calculations:

The experimental data provided in reference 4, has bandgap changes in a BLG transistor from 0eV to .25eV as the vertical electric displacement in double gate contacts increases from 0 to 3.0 V/nm. The experimental data in reference 4 uses the same bilayered graphene and dielectric material thicknesses as this study. With the known values of the electric displacement, dielectric constant, and dielectric thickness, the density of states or DOS within the bilayer graphene can be determined. DOS was calculated using the equation from reference 1 below:

$$DOS = \frac{1}{2\pi\hbar}\left(\frac{2m^*}{\hbar} + \sqrt{\frac{2m^*}{E - E_c}}k_{min}\right) \qquad (1)$$

With the $E - E_c$ being the conduction band energy from Fermi level, $\hbar$ being reduced Planck's constant, m^* being the effective mass, and k_{min} being the minimum Dirac point of the BLG. The k_{min} and m^* are determined in reference 1 using an interlayer hopping energy of -0.365eV within the BLG and an in-plane hopping energy of -3.033eV.
The DOS decreases from 6.82 x 10^{19} cm^{-2} to 3.01 x 10^{19} cm^{-2} as the electric displacement changes from 0 to 3.0V/nm. Translating the electric displacement to gate voltages provides a range of 0.084V to 1.0V. The gate

voltages are under a flatband assumption within the BLG layer. The electron concentration of the BLG as the gate potential between the high impedance layer and ground plane increase are calculated in the equations below.

$$N = \int_0^{E_c} N(E)F(E)dE, \quad N = \int_0^{E_c} DOS\left[\frac{1}{1+e^{-(E-E_F)/_{kT}}}\right]dE \tag{2}$$

The electron mobility for BLG is assumed to be 100,000 cm^2/Vs. The *T* represents the temperature in Kelvin, which for this study will be at room temperature. The k_B, represents the Boltzmann's constant. Knowing the permittivity of the dielectric layers, susceptibility of BLG, and antenna width, the total impedance per unit length and current density can be determined using the equations below. The unit length x is 312.5 microns as mentioned in the previous section of this study. The second and third terms in equation (3) represent the inductance impedance and capacitance impedance, respectively. Equations (3) and (4) calculate the change in impedance across the antenna length as the DC bias changes the conductivity per unit length. The results of the impedance on one unit length as the conductivity changes are in Figure 4. The total impedance across the antenna is calculated in unit lengths across a quarter of a wavelength in each x-direction of the center feed as described in Figure 1 above.

$$Z(x) = Z_{BLG} + Z_L + Z_C, \quad -\frac{\lambda}{4} < x < \frac{\lambda}{4} \tag{3}$$

$$Z(x) = \frac{1}{W\sigma t_{BLG}} + 2\pi f\left(\frac{\mu_r \mu_0 d}{W}\right)|x| + \frac{1}{2\pi f\left(\varepsilon_r \varepsilon_0 \frac{W|x|}{d}\right)} \tag{4}$$

$$I(x) = \frac{V_0}{Z(x)} \tag{5}$$

Where W, represents the width of the BLG antenna and V_0, represents the initial input RF signal amplitude at a value of 10V. The *f* is the frequency of the signal, *d* is the 1nm thickness of the dielectric. The t_{BLG} represents the .8nm thickness of the BLG transmission layer. Equation is RF signal at the center feed directly proportional to the impedance across the antenna length to yield the current density. Equation (6) determines the far field intensity at different elevation angles as different DC biases are applied to all 32 contacts simultaneously. With equation (7), the far field intensity per unit length can be calculated for different sequences of DC biases applied along the antenna. The k represents the wave number of the signal and Z_0 is the air impedance.

$$U = \frac{Z_0}{2}\left(\frac{kI(0)L}{4\pi}\right)^2 sin^2\theta \tag{6}$$

$$dU = \frac{Z_0}{2}\left(\frac{kI(x)dL}{4\pi}\right)^2 sin^2\theta, \qquad k = \frac{2\pi}{\lambda} \tag{7}$$

The dL in equation (7) above is equivalent to (x) length in this study. The different sequences of applying vertical fields to each of the 32 DC contact segments are decrease the DC bias on each contact from the center of the dipole to the each end, and increasing the DC bias on each contact from center dipole to each end.

Results:

The tool used in this study is MATLAB R2009A conducting all the calculations of the above equations. As mentioned in the design and structure section of this study, experimental data from reference 4 contains 7 data points of the bandgap of bilayered graphene increases as the electric displacement increases. When implementing that experimental data into the equation (1) and (2), the electron concentration in Figure 2 decreases as the DC bias increases. This verifies typical semiconductor behavior with the bandgap increasing reducing the ability of electrons to jump into the conduction band. The electron concentration being inversely proportional to the electron mobility and electron charge can yield the conductivity of the bilayered graphene material shown in Figure 3 below.

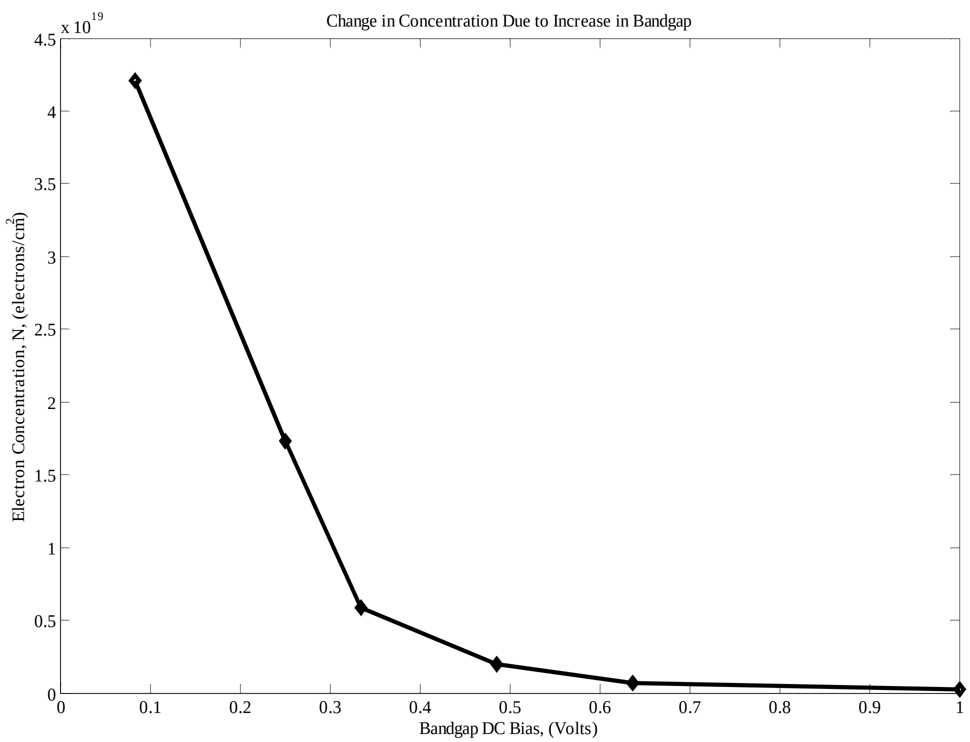


Figure 2, 2DEG electron concentration of the bilayer graphene material as the gate voltage is changing the bandgap of the bilayer graphene. As the bandgap increases the concentration drops.

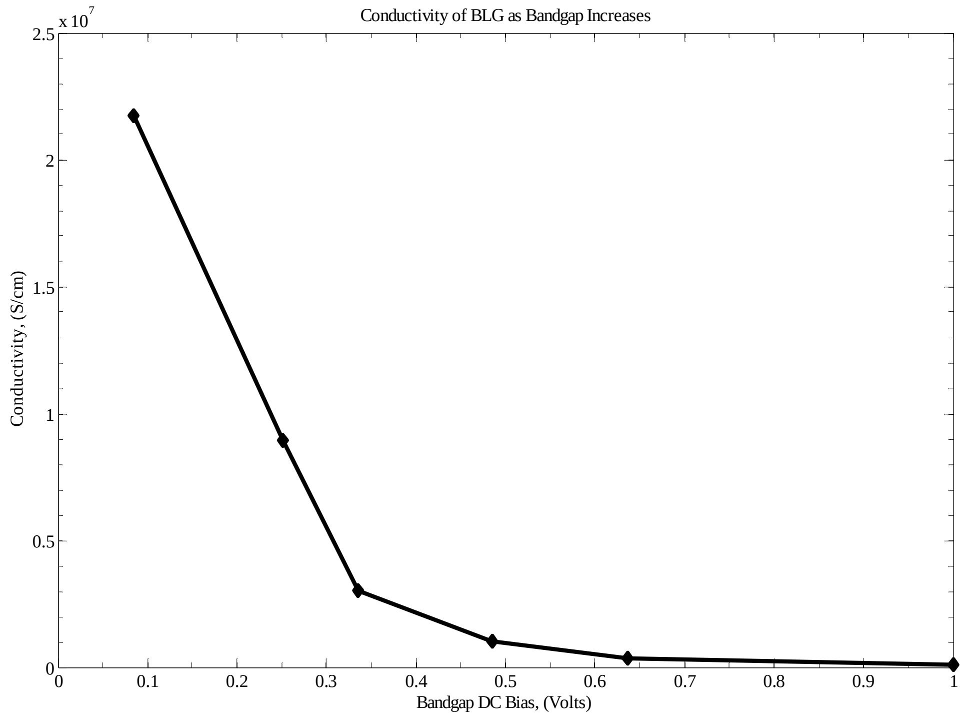


Figure 3, conductivity change as the bandgap increases in the bilayered graphene transmission line

The conductivity of the BLG material along with the other parameters of the microstrip dipole antenna are fed into equations (3) and (4) for calculating the impedance per unit length across the entire half wavelength antenna. Figure 4 shows the change in impedance across unit length as the DC bias increases.

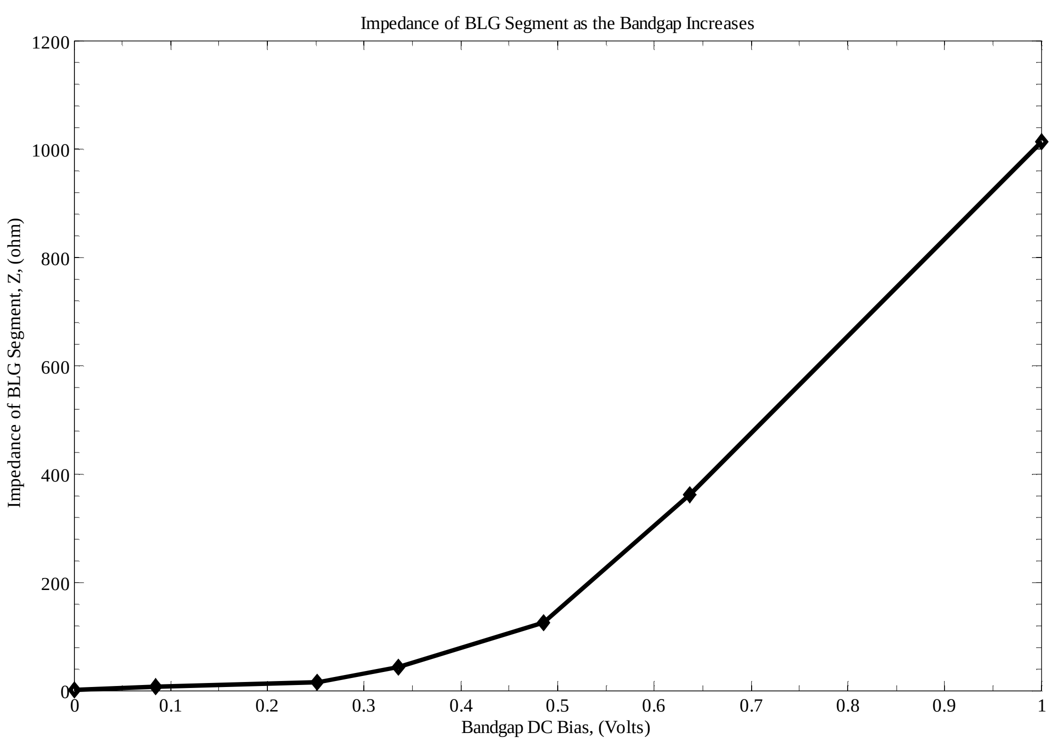


Figure 4, impedance per unit length at the gate voltage increases

The impedance data displayed in Figure 4 includes the inductance and capacitance over one unit length as the DC voltage increases. The maximum electric displacement in the experimental data is 3.0V/nm, which produces 0.25eV gap from Fermi level to conduction band, translates to 1.0V producing 1kohm/per unit length as shown in Figure 4 above. Feeding equation (3) and (4) per unit length across half the antenna length at different DC bias amplitudes into (5) yield the current density results in Figure 5 below. Each line in Figure 5 represents the different DC amplitudes that change the bandgap of the BLG material.

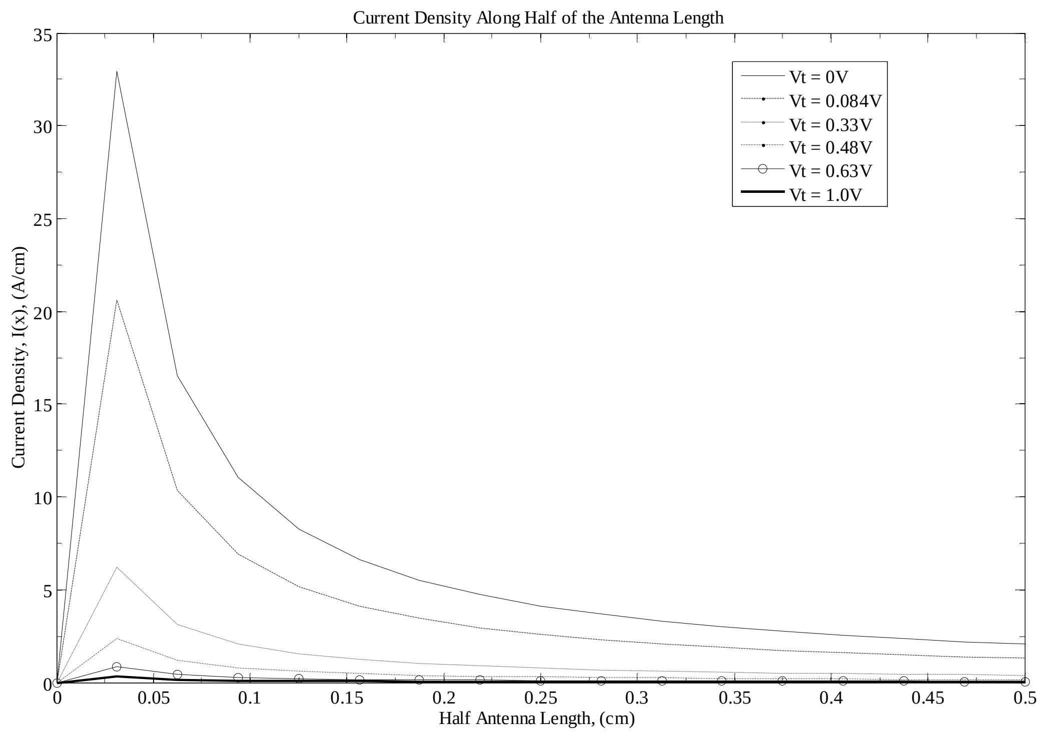


Figure 5, Current Density along the half of the dipole antenna

The results of (6) are displayed in Figure 6 and 7 below. Figures 6 and 7 show the maximum normalized magnitude and the minimum normalized magnitude, respectively. The radiation intensity decreases in magnitude, but stays constant in beam width as the DC bias increases on all top contacts simultaneously. Data is show from elevation angles of 0 to 180 degrees due to microstrip structure with a low impedance ground plane at the very bottom. The calculated results of (7) are displayed in Figure 8 and 9 on the different sequences will be displayed in non-polar plot give that the far field intensity changes per unit length. The results have shown so far that the impedance increases and the DC bias increases, and the impedance decreases as the DC bias decreases. Figure 8, is the DC bias decreasing from the center feed to the each end of the antenna on each of the 32 top contacts. Figure 9, shows the results of the DC bias increasing from the center feed to the each end of the antenna on each of the 32 top contacts. At 30 degrees elevation the magnitude of the intensity is minimum and at 90 degrees elevation the intensity is maximum. Both plots in Figure 8 and 9 are normalized by the maximum intensity with no DC bias. The results show that the DC bias decreases from center to each end the beam width gets wider, and the beam width gets narrower when the DC bias increase from center to each end.

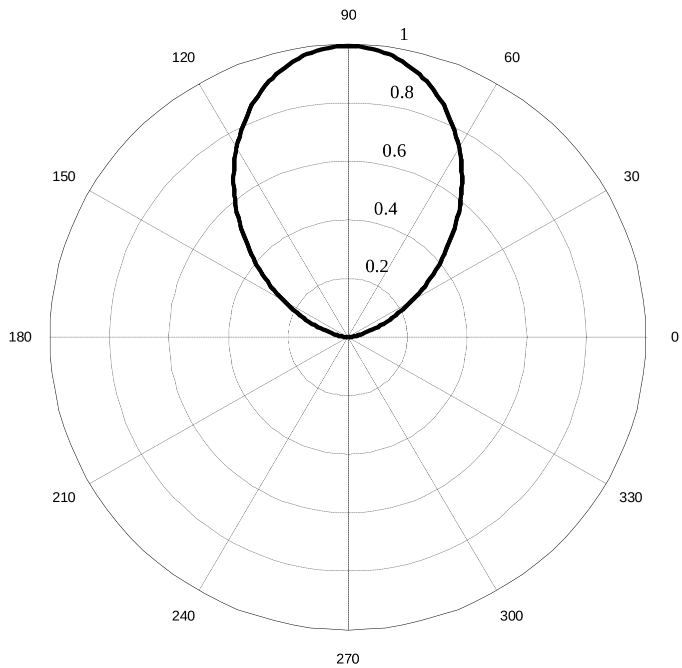


Figure 6, far field intensity vs. elevation angle radiation pattern normalized by maximum intensity with no DC voltage applied to BLG

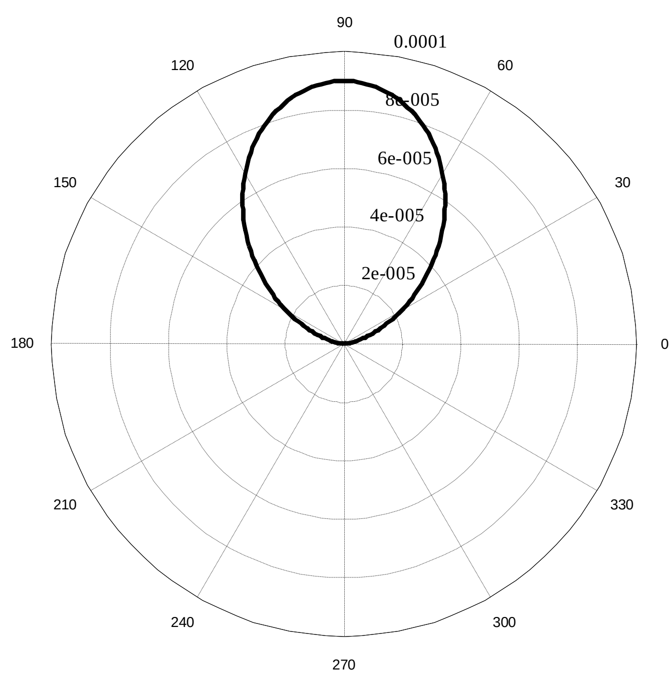


Figure 7, far field intensity vs. elevation angle radiation pattern with a DC Voltage of 1V applied to all the top contacts. This plot is normalized by maximum intensity with no DC voltage.

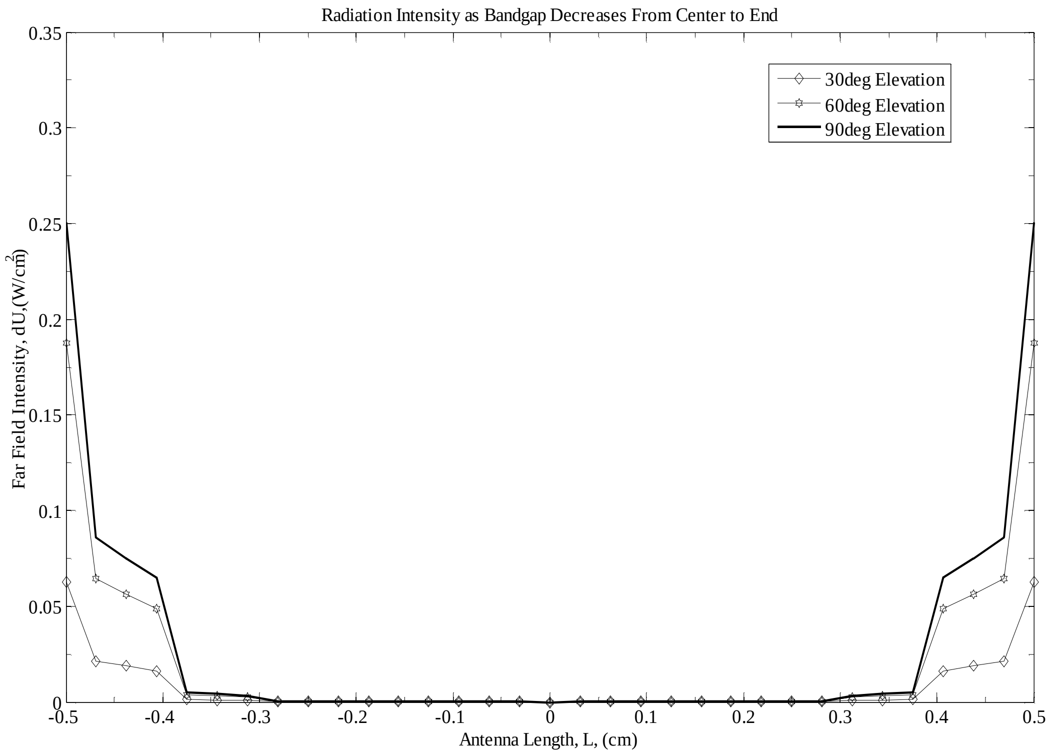


Figure 8, far field intensity vs. length of BLG microstrip dipole antenna with the gate voltages decreasing from center to end

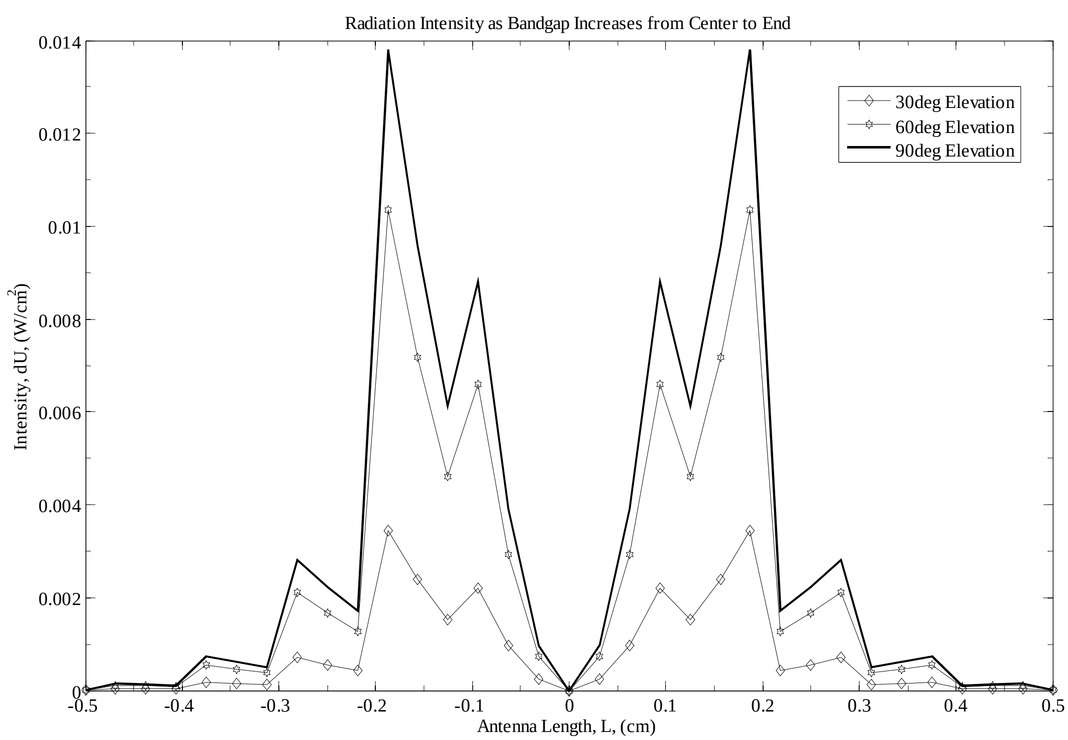


Figure 9, far field intensity vs. length of BLG transmission line with DC voltage increases from center to end

Conclusions:
The results of this study show that it is possible to tune a bilayered graphene as an antenna in a microstrip structure. The results show that applying vertical DC fields to the outer top contacts can narrow the beam width of the dipole radiation, and widen the beam by applied DC fields to the inner top contacts. Since the magnitude of the radiation decreases by a factor of 10^6 from 0V DC to 1V DC, a binary signal can be used to tune the antenna by just applying 1 and 0 bits. Since there are 32 total top layer gate contacts, a 32 bits digital signal could be used to tune this type antenna. Future studies will determine how to apply a digital signal along with high microwave input signal to tune the antenna for filtering, beam steering, or beam forming. The benefits of this research can be an asset to smart munitions in the military and mobile wireless communications devices in the commercial industries.

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